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Some Considerations on the Thermostat Hypothesis

A symposium on the *Regulation of Tropical Sea Surface Temperatures and Warming of the Tropical Ocean Atmosphere System* was held 18–19 January 1995 at the 75th Anniversary Meeting of the American Meteorological Society in Dallas, Texas. One of the purposes of this symposium was to assess the validity of the "thermostat hypothesis" that was put forward by Ramanathan and Collins (1991, RC hereafter) to explain the manner in which the ocean–atmosphere system limits large-scale sea surface temperatures (SSTs) to the observed maximum value of about 303 K. Central to this hypothesis is the strong negative feedback to SST warming produced by cloud shielding of surface insolation by highly reflective cirrus anvil clouds associated with tropical deep convection. This hypothesis has provoked considerable controversy regarding the primary feedback mechanisms that limit the maximum SST and even the feedbacks that regulate tropical SSTs in general, both in the present climate and under a scenario of global warming.[1] The scientific importance of understanding the nature of these climate feedbacks, and thus reconciling this debate, drew support from the National Science Foundation and the Department of Energy. These two agencies funded a one-month field experiment during March of 1993 in the tropical Pacific, the Central Equatorial Pacific Experiment (CEPEX 1992), in order to directly measure quantities important in the assessment of this hypothesis. With the advent of data from this experiment, as well as from the complimentary and more ambitious Tropical Oceans–Global Atmosphere (TOGA) Coupled Ocean–Atmosphere Response Experiment (COARE) (Webster and Lukas 1992), we can begin to assess how this climate hypothesis is fairing under more formidable empirical scrutiny.

Prior to the thermostat hypothesis, the prevalent theory that accounted for limiting SST in the Tropics was based on Newell (1979), which required the evaporative heat flux to have a mean value of about 200 Wm^{-2} over the warmest oceans and a negative feedback strength of about 30 Wm^{-2} per degree of SST warming. This hypothesis was modified slightly by Graham and Barnett (1987), who suggested—based on the observed increase of large-scale deep convection as SST increases above ~300 K—that cloud shielding, in addition to evaporation, plays a role in limiting SST in the Tropics. These ideas were followed by the "thermostat hypothesis," which RC based on the following three premises. First, the "super greenhouse effect" results in the longwave radiation component ceasing to function as a negative feedback on SST growth in the upper range of tropical SSTs. Second, local analysis of the changes in SST versus top-of-the-atmosphere, shortwave cloud

[1] Including Heymsfield and Miloshevich (1991); Stephens and Slingo (1992); Wallace (1992); Fu et al. (1992, 1993); Ramanathan and Collins (1992, 1993); Waliser and Graham (1993); Hartmann and Michelsen (1993); Washington and Meehl (1993); Arking and Ziskin (1994); Lau et al. (1994a,b); Ramanathan et al. (1994); Waliser et al. (1994); Inamdar and Ramanathan (1994); Pierrehumbert (1995); Waliser (1996).

forcing occurring in association with the 1985–87 El Niño–Southern Oscillation "cycle" indicates cloudiness is acting as a negative feedback with a magnitude of about 22 $Wm^{-2} K^{-1}$. Third, surface evaporation is unable to function as a limiting mechanism because 1) evaporation adds moisture to the boundary layer and thus enhances the super greenhouse effect, and 2) water vapor is actually imported into the warmest ocean regions and thus evaporation tends to be weak there. Based on these facts and inferences, Ramanathan and Collins (1991) concluded that SST-induced changes in shortwave cloud forcing accounted for the primary negative feedback, which limits SSTs to about 303–305 K.

The ensuing debate regarding the thermostat hypothesis has primarily stemmed from two contentions. The first retains the idea that evaporation,[2] more so than shortwave cloud forcing, is the fundamental mechanism limiting SST (e.g., Wallace 1992; Fu et al. 1992; Hartmann and Michelsen 1993). The second emphasizes the central role of the large-scale atmospheric circulation, particularly the coupling between the large-scale circulation and the local environment (e.g., Wallace 1992; Hartmann and Michelsen 1993; Lau et al. 1994a; Pierrehumbert 1995). With respect to the first contention, that is, the relative roles of evaporation and shortwave cloud forcing, data from both the CEPEX and COARE experiments indicate that the cooling effects due to clouds play as significant a role as evaporation in cooling the western Pacific warm pool. This is evident in both mean and high-frequency data, as well as from estimates of the shortwave cloud-forcing and evaporation feedbacks on SST. For example, recent estimates of the surface energy budget in the western Pacific (e.g., Ramanathan et al. 1995) indicate that the cooling effects due to clouds and evaporation are each on the order of 100 Wm^{-2}. Further, hourly data from the Improved Meteorological (IMET) instrument buoy (R. Weller and S. Anderson 1995, personal communication) deployed during COARE show that while latent heat flux ranges up to about 400 Wm^{-2}, shortwave cloud forcing ranges up to about 950 Wm^{-2}, with mean values for these quantities during the COARE period being about 110 and 105 Wm^{-2}, respectively (Waliser et al. 1996). Finally, the evidence suggests that the local negative feedback from cloud forcing tends to strengthen with SST (e.g., Graham and Barnett 1987; Collins et al. 1995), while for evaporation, it tends to weaken (Zhang and McPhaden 1995).

To understand why in the context of high SST the evaporative feedback gives way to the shortwave feedback in a local sense, yet why it is necessary to consider the large-scale and remote effects of the atmosphere in this problem, we can examine an idealized situation in which the atmosphere overlies an ocean of uniform temperature. If we "insert" a large-scale positive temperature anomaly in the ocean-surface mixed layer, how does the system respond? In the region of warmer SST, the system will initially try and equilibrate through enhanced surface fluxes of latent and sensible heat. These enhanced fluxes will initiate a low-level atmospheric convergence over the region of maximum SST (Lindzen and Nigam 1987; Gill 1980; Zebiak 1986). Keep in mind, however, that the amount of heat and moisture removed from the ocean in order to initiate this circulation results in a negligible change in the ocean mixed-layer temperature due to the drastic difference in the heat capacities of water and air. Associated with this low-level convergence are 1) strong upward vertical motion over the region of warmest SST with compensating, weak downward motion elsewhere; 2) a reduction in the mean value of the surface wind speed over the region of warmest SST relative to the surrounding areas (since the wind direction must change sign across the SST anomaly); and 3) the transport of low-level moisture into the region of high SST. Of these three effects, the first and third act to enhance the cloud shortwave forcing over the local region of high SST relative to the surrounding areas, while the second and third have the opposite effect on the evaporation.

The observational results discussed above, along with the local perspective provided by the idealized scenario, are consistent with the hypothesis that shortwave cloud forcing, more so than evaporation, provides the primary negative feedback that limits SST extremes in the Tropics. However, in arriving at an understanding of why these two feedbacks behave as observed, it has been necessary to consider the modifications to the atmospheric circulation produced by the SST anomaly, modifications that occur over a length scale much larger than the length scale of the SST anomaly. This necessity forms much of the basis for the second contention with the thermostat hypothesis: even though a region of extreme SST will,

[2] Evaporation hypotheses may rely on contributions from sensible heat flux as well due to its dynamic and thermodynamic similarities with latent heat flux. However, because this term is typically an order of magnitude smaller it is often not discussed explicitly.

in general, initiate a locally strong negative cloud feedback, the inherent coupling of this feedback to the large-scale circulation plays a critical role in determining the strength of this as well as other feedbacks in the system. For example, the anomalous circulation associated with the region of extreme SST fits within the context of an even larger-scale global circulation, the strength and direction of which will determine the degree this feedback can develop (e.g., Hartmann and Michelsen 1993; Lau et al. 1994b). The temperature and moisture content of the converging air will also have an influence over the resulting cloudiness and, more importantly, the local rates of evaporation. These quantities are to a large degree determined by processes remote to this local region of high SST (e.g., Pierrehumbert 1995). Finally, added to the above complexity and uncertainty is how the local winds and surface fluxes will influence the response of the ocean. As of now, evidence suggests that the western Pacific warm pool only exports on the order of 10–30 Wm^{-2} and, thus, plays only a modest role in closing the surface heat budget (Gent 1991; Young et al. 1992). However, because the atmosphere and ocean are so tightly coupled in the Tropics and because there are significant nonlinearities in the system, the exact role of the ocean in this process is only beginning to be explored. Important to the present concern is, how does this 10–30 Wm^{-2} fluctuate in response to a large-scale SST warming?

Given the drastic difference in complexity between the real climate system and the thermostat hypothesis, which attempts to describe one aspect of it, it is difficult to ascribe validity, particularly when 1) factoring in remote effects on the local high SST environment; 2) assessing the "thermostat's" role in regulating, versus limiting, the present climate's SST; or 3) extending its applicability to future climate changes. Of less difficulty, however, is assessing the qualitative contributions made by the hypothesis. Foremost, the hypothesis has underscored the importance of cloud-forcing feedbacks in high SST regimes relative to the more conventional mechanism of evaporation. By doing so, it has challenged much of the tropical climate community to reevaluate their understanding of the surface energy budget in these regions and reconsider the relative strengths of the feedbacks that keep this system at the observed equilibrium. On the practical side, the controversial nature of the hypothesis has provoked a host of alternative propositions and motivated the acquisition of data that can be used to test these propositions as well as future models and theories. Finally, from a pedagogical standpoint, the thermostat hypothesis has and can continue to serve as a useful paradigm in our efforts to further unravel the complex nature of our climate.

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